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(54) **Optical waveguide device**

Optische Wellenleitervorrichtung

Dispositif optique à guide d'onde

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Description

[0001] The present invention relates to an optical waveguide device, and more particularly to an optical waveguide device such as a modulator, switch, distributor, or the like, used in optical communication apparatus.

[0002] A typical optical waveguide device used in an optical switch, an optical modulator, or the like, is constituted such that an electric field is applied to an optical waveguide formed on a surface of a substrate consisting of electrooptical crystal such as lithium niobate ($LiNbO_3$), or the like, so as to change a refractive index, and thus switching or phase modulation of a light signal traveling through the optical waveguide can be carried out.

[0003] In particular, an optical waveguide device typically includes an optical waveguide formed on a surface of a substrate having an electrooptical effect and a pair of electrodes formed on corresponding regions above the optical waveguide and receiving a driving electric signal thereacross. A distribution of electric field occurring in a vicinity of the optical waveguide by an application of the electric signal is greatly changed in accordance with a change in a frequency of the electric signal.

[0004] As an example of the optical waveguide device, a Mach-Zehnder type modulator is well known. A modulator of this type includes at least an optical waveguide formed on a surface of a Z-cut $LiNbO_3$ substrate and a pair of asymmetrical electrodes formed on corresponding regions above the optical waveguide. In such a structure, charges collected on the surface of the $LiNbO_3$ substrate by the pyroelectric effect act on the asymmetrical structure of the electrodes and thus a disadvantage occurs in that the distribution of charges is made uneven and an adverse influence is exerted on characteristics of the device.

[0005] Also, since the distribution of resistance, dielectric constant and capacitance of each portion of the structure or partial fine structure is delicately changed in accordance with the process conditions, the electrical equivalent circuit accordingly becomes complicated. This results in a problem in that a direct current (DC) component of an electric signal applied across the electrodes greatly changes an application manner of the electric field with a long-term time constant and the optical response is also accordingly changed. This phenomenon is called a DC drift.

[0006] Both JP-A-62 073 207 and JP-A-1 302 325 disclose an optical waveguide device in which at least two metal electrodes are formed on a buffer layer overlying a $LiNbO_3$ substrate.

[0007] It is therefore desirable to provide an optical waveguide device capable of suppressing a DC drift thereof to effectively compensate for fluctuation in operational characteristics due to the DC drift, stress, or the like.

[0008] In the applicant's co-pending European patent application No. 91301729.9 there is proposed an optical waveguide device in which a third electrode other than the pair of driving electrodes is provided on a region spaced by a predetermined distance from the pair of driving electrodes formed on corresponding regions above the optical waveguide. The third electrode may receive a DC or low frequency voltage, or may be grounded under predetermined layout conditions of each electrode.

[0009] In an optical waveguide device formed on an electrooptical crystal substrate having a pyroelectric effect, it is preferable that a semiconductive layer of, e.g., silicon (Si) is formed on a buffer layer so as to make uniform a distribution of charges occurring in the vicinity of the surface of the optical waveguide. In this case, in a structure having a narrow signal line electrode and a wide grounding electrode, a potential on the semiconductive (Si) region on the outside of the signal line electrode (i.e. on the opposite side of the grounding electrode) is uniformly made equal because the silicon (Si) layer acts as a conductor in a low frequency band. As a result, a drawback arises in that the electric field to be concentrated on the vicinity of the signal line electrode is dispersed into the outside semiconductive (Si) region and thus it is not effectively applied to the optical waveguide.

[0010] To cope with this drawback, a third electrode may be provided on the outside of the signal line electrode, i.e. on the opposite side of the grounding electrode. By this structure, it is possible to cause a voltage drop in proportion to the distance between the signal line electrode and the third electrode and thus concentrate the dispersed electric field on the vicinity of the signal line electrode. Also, by suitably changing the thickness of the silicon (Si) layer between the signal line electrode and the third electrode, it is possible to change a distribution of resistance therebetween to regulate a distribution of the voltage drop and thus concentrate the electric field more effectively. On the other hand, when a high frequency electric signal is applied to the pair of driving electrodes, charges in the silicon (Si) layer cannot follow a change in the high frequency electric signal and thus the semiconductive layer functions as a dielectric. Also, by disposing the third electrode on a region spaced from the signal line electrode by a sufficient distance, it is possible to reduce the influence exerted on the characteristic impedance of the traveling wave electrode. In the afore-mentioned co-pending application the applicants propose the use of a semiconductor layer having a relatively low resistance in place of a conductor as the third electrode, thereby gaining the same effect as above and further reducing the influence exerted on the characteristic impedance.

[0011] Although the above structure premises that the third electrode is grounded, the third electrode may receive a voltage signal. In this case, more effective advantages can be obtained. Namely, by applying a DC or low frequency voltage to the third electrode, it is possible

to compensate for a fluctuation in operational characteristics occurring due to a DC drift, mechanical stress, or the like. In this case, it is preferable that a semiconductor layer consisting of material having a relatively high resistance, e.g. silicon (Si), is formed close to the signal line electrode. The semiconductor layer may receive a voltage directly from an external power source, or may receive the voltage via a conductor layer, which is formed on the semiconductor layer at a position spaced from the signal line electrode by a sufficient distance such that its presence does not greatly affect a characteristic impedance of the traveling wave electrode. By applying the voltage directly or indirectly to the semiconductor layer, it is possible to change a refractive index of the optical waveguide beneath the signal line electrode and thus compensate for a fluctuation in operational characteristics. In this case, the semiconductive layer functions as a conductor with respect to a low frequency voltage and functions as a dielectric with respect to a high frequency voltage. Accordingly, the presence of the semiconductive layer has less influence on the characteristic impedance in the high frequency band of the applied voltage. Also, another semiconductive layer may be formed all over the buffer layer so as to improve temperature characteristics. In this case, by decreasing the thickness of the semiconductive layer in the vicinity of the signal line electrode and concentrating the electric field on the thinly formed portion, it is possible to realise the same effect as above.

[0012] In the present application the applicants propose an alternative solution which is an improvement of a conventional Mach-Zehnder type optical waveguide device and which is based on the principle described below.

[0013] Electrodes constituting optical modulators, optical switches, or the like, are formed to have a low resistance and thus enable a high speed operation. To this end, it is preferabe to use a material having a high electric conductivity such as copper (Cu), gold (Au), or the like, and increase the thickness of the electrode. Where a material having a relatively high resistance such as a silicon (Si) layer is adjacent to the material having a high electric conductivity, it functions in different phases in accordance with the selection of the resistance value. Namely, when a DC or low frequency voltage is applied to the signal line electrode, the silicon (Si) layer is kept in a state of equal potential in the same manner as the conductor (electrode). Contrary to this, where the frequency of the signal propagating on the signal line electrode is gradually increased, charges in the silicon (Si) region cannot follow a high speed change in the signal, and thus, a region in which charges can follow the high speed change in the signal is gradually limited to the vicinity of the conductor (electrode). In other words, an effective shape of the electrode is greatly changed between the low frequency band and the high frequency band. By utilizing the change in the effective shape of the electrode, it is possible to constitute a device having various functions.

[0014] To realize a high speed switching or modulation, a pair of electrodes for a traveling wave are normally employed. According to an improved structure, a semiconductive layer comprised of silicon (Si) is formed between the pair of electrodes and the buffer layer. The semiconductive layer is separated into two regions in the center of the corresponding region thereof between the electrode for signal line and the electrode for grounding. By this constitution, an electric field by a DC or low frequency component of the applied signal is concentrated on the separated portion and a component of the electric field in the vicinity of the optical waveguide is weakened. Accordingly, even if the DC or low frequency component is changed due to a DC drift, it is possible to suppress a fluctuation in operational characteristics. On the other hand, where a high frequency electric signal is applied to the pair of electrodes, charges in the silicon (Si) layer cannot follow a change in the high frequency electric signal and thus the silicon layer functions as a dielectric. In this case, since the electric field is applied across the pair of electrodes, it effectively acts on the optical waveguide.

[0015] Also, even in the case that a thinly formed conductive layer is substituted for the above-mentioned semiconductive layer, it is possible to realize the same effect as above. This is because even the conductor has a larger volume resistivity than zero and the resistance value is increased with a decrease in the thickness of the conductive layer.

[0016] Thus, according to a first aspect of the present invention there is provided an optical waveguide device comprising: an optical waveguide formed on a surface of a substrate having an electro-optical effect; a pair of electrodes operatively connected and arranged to receive a driving electric signal thereacross; a buffer layer formed all over the said surface of said substrate including the optical waveguide; and a semiconductive layer formed between the buffer layer and the pair of electrodes, a part of the said semiconductive layer which corresponds to the gap between the pair of electrodes being of reduced or zero thickness; wherein a change in frequency of the driving electric signal applied across the pair of electrodes when the device is in use brings about a corresponding change in a distribution of an electric field which occurs in the vicinity of the optical waveguide, and wherein, when a low frequency electric signal is applied to the pair of electrodes, the electric field is concentrated on the said part of the said semiconductive layer.

[0017] According to a second aspect of the present invention there is provided an optical waveguide device comprising: an optical waveguide formed on a surface of a substrate having an electro-optical effect; a pair of electrodes operatively connected and arranged to receive a driving electric signal thereacross; a buffer layer formed all over said surface of said substrate including the optical waveguide; and a first semiconductive layer,

formed between the buffer layer and the pair of electrodes, and a second semiconductive layer, formed between the first semiconductive layer and a signal line electrode of the pair of electrodes, the second semiconductive layer having a specific resistance different from that of the first semiconductive layer and having a broader width than that of the signal line electrode; wherein a change in frequency of a driving electric signal applied therebetween when the device is in use brings about a corresponding change in a distribution of an electric field which occurs in the vicinity of the optical waveguide.

[0018] Reference will now be made, by way of example, to the accompanying drawings, in which:

Figs. 1A and 1B show plan and sectional views, respectively, of a structure of a prior art Mach-Zehnder type modulator;
Figs. 2A and 2B show plan and sectional views, respectively, of an optical waveguide device (optical modulator) embodying the first aspect of the present invention;
Fig. 3 shows a sectional view of a first modification of the structure shown in Figs. 2A and 2B;
Fig. 4 shows a sectional view of a second modification of the structure shown in Figs. 2A and 2B;
Fig. 5 shows a sectional view of a third modification of the structure shown in Figs. 2A and 2B;
Figs. 6 shows a sectional view of an optical waveguide device (optical modulator) embodying the second aspect of the present invention;
Fig. 7 shows a sectional view showing a first modification of the structure shown in Fig. 6; and
Figs. 8A and 8B show plan and sectional views, respectively, of a second modification of the structure shown in Fig. 6.

[0019] Figures 1A and 1B show a structure of a prior art Mach-Zehnder type modulator. Note, Fig. 1B shows a sectional structure along the line A-A' in Fig. 1A. The illustrated structure shows an example using asymmetrical electrodes for a traveling wave.

[0020] In the drawings, reference 1 denotes a Z-cut $LiNbO_3$ substrate and reference 2 denotes an optical waveguide including two-forked optical waveguides 2a and 2b. The optical waveguide 2 (2a, 2b) is formed by effecting a striplike patterning of a Titanium (Ti)-deposited layer formed on a surface of the substrate 1 and then effecting a thermal diffusion of the Titanium into the substrate 1. Thus, the optical waveguide 2 (2a, 2b) has a larger refractive index than that of the substrate 1.

[0021] Also, to prevent light propagating through the optical waveguide from being absorbed in driving electrodes (a signal line electrode 5 and grounding electrode 6), a dielectric buffer layer 3 is formed between the electrodes 5, 6 and the optical waveguide 2. The buffer layer 3 is translucent and has a smaller refractive index than that of the optical waveguide 2. The buffer layer 3 is comprised of, for example, silicon dioxide (SiO_2). The dielectric layer 3 electrically functions as a capacitance containing relatively high resistance material.

[0022] In an optical waveguide device using a substrate of Z-cut $LiNbO_3$, a disadvantage occurs in that charges collected on the surface of the substrate by the pyroelectric effect act on the asymmetrical structure of the electrodes formed on the buffer layer and thus an uneven distribution of charges is formed, which has an adverse influence on characteristics of the optical waveguide device. In view of this, a semiconductive layer 4 comprised of, for example, silicon (Si) is formed between the buffer layer 3 and the electrodes 5, 6 and all over the buffer layer 3 (see Fig. 1B). By this structure, it is possible to make uniform the distribution of surface charges occurring due to a change in temperature or the like and stabilize the characteristics of the optical waveguide device.

[0023] Furthermore, since the optical waveguide 2 is formed by diffusing the Titanium with high temperature into the $LiNbO_3$ substrate 1, its resistance, dielectric constant and capacitance are different from those of the bulk portion of the substrate 1. Additionally, a resistance of the surface of the $LiNbO_3$ substrate 1 is different from that of the bulk portion thereof due to the diffusing process. In view of the complicated distribution of the resistance, dielectric constant and capacitance of the above layers and partial fine structure, the electrical equivalent circuit also becomes complicated. As a result, a problem occurs in that a DC component of an electric signal applied across the electrodes 5, 6 greatly changes an application manner of the electric field with a long-term time constant in accordance with the process conditions and the optical response characteristics are also accordingly changed. Namely, a DC drift is caused.

[0024] To cope with the problem, there have been taken measures to connect the electrodes 5, 6 of the modulator to an external power source by way of capacitance coupling and thus prevent a DC component of the power source from being directly applied to the modulator, or measures to connect a biasing DC power source to the electrode for signal line 5 by means of capacitance coupling and thus compensate a DC drift occurring due to some causes.

[0025] According to the measures to employ an external power source by way of capacitance coupling, however, a drawback occurs in that the device is brought to an electrically open state seen from the power source and thus an adverse influence is exerted on the operation of the power source. A disadvantage also occurs in that an available frequency band of the power source is limited in dependence on the capacity thereof. On the other hand, according to the measures to employ a biasing DC power source by way of capacitance coupling, a drawback occurs in that a characteristic impedance of the traveling wave signal line electrode fluctuates and thus it is impossible to satisfactorily carry out the modulation operation.

[0026] Also, where a stress is applied to the optical

waveguides for some reason, the refractive index of the optical waveguides normally changes resulting in a fluctuation in operational characteristics of the modulator. To cope with this disadvantage, there has been heretofore taken measures to add a DC voltage to the application voltage so as to cancel a change in the refractive index occurring due to the stress.

[0027] However, to take the measures to add a DC voltage to the application voltage is often difficult from a viewpoint of the limit of the dielectric strength of the DC power source.

[0028] In view of the above problems, a structure or means other than the electrodes provided for switching or modulation needs to be provided for suppressing a DC drift and compensating for a fluctuation in operational characteristics due to the DC drift, stress, or the like.

[0029] As shown in Figs. 2A and 2B, the structure illustrated in Figs. 1A and 1B may be modified in accordance with the first aspect of the present invention so as to have a semiconductive layer (4a, 4b) formed between the buffer layer 3 and the electrodes 5 and 6. The semiconductive layer is comprised of silicon (Si) and has a thickness of approximately 0.2 μm, and is separated into two regions 4a and 4b in the center of the corresponding region thereof between the electrodes 5 and 6. The gap between the separated portions 4a, 4b, indicated by reference P, is selected to be 1 to 4 μm. Note, each semiconductive layer 4a, 4b has a broader width than that of the corresponding electrode 5, 6. In this case, a specific resistance of the semiconductive layer (4a, 4b) can be designed and selected over a wide range from 0.001 to 100000 Ωm. Where the present optical modulator is used in a frequency of 5 to 6 MHz or more, the specific resistance is preferably selected to be 100 Ωm. Of course, the specific resistance is altered in accordance with a thickness of each layer, a layer-to-layer distance, a distance between each electrode, and the like.

[0030] By adopting the above structure, components of a DC voltage or a low frequency voltage of 50 to 60 Hz applied across the electrodes 5, 6 are concentrated on the separated portion P and thus do not substantially affect the characteristic impedance of the optical waveguide 2 (2a, 2b). On the other hand, where a high frequency voltage of approximately 5 to 6 MHz is applied across the electrodes 5, 6, charges cannot easily follow a change in the voltage and thus the semiconductive layer (4a, 4b) functions as a dielectric. Namely, since the high frequency voltage is applied between the electrodes 5 and 6, it is possible to effectively change the refractive index of the optical waveguide 2 (2a, 2b). Therefore, according to the present example, it is possible to disregard a DC component of the applied voltage and thus suppress the influence of DC drift.

[0031] Figure 3 shows a first modification of the embodiment shown in Figs. 2A and 2B.

[0032] In the present example, the semiconductive layer 4a is formed only in the vicinity of the electrode for signal line 5. Since the width of the semiconductive layer 4a formed under the electrode 5 can be arbitrarily designed and selected, it is possible to realize better frequency characteristics.

[0033] Figure 4 shows a structure of a second modification.

[0034] In the present example, in place of the separated semiconductive layers 4a, 4b shown in Figs. 2A and 2B, a semiconductive layer 4c comprised of silicon (Si) is formed between the buffer layer 3 and the electrodes 5 and 6 and all over the buffer layer 3. The semiconductive layer 4c has a thinly formed portion Q in the center of the corresponding region thereof between the electrodes 5 and 6. By this structure, a DC component or a low frequency component of the voltage applied across the electrodes 5, 6 is concentrated on the thinly formed portion Q and thus it is possible to gain the same effect as in Figs. 2A and 2B.

[0035] Figure 5 shows a structure of a third modification, which is a combination of the example of Fig. 3 and the example of Fig. 4.

[0036] In the present example, since the semiconductive layer 4c is formed only in the vicinity of the signal line electrode 5, it is possible to realize better frequency characteristics as in the example of Fig. 3.

[0037] As shown in Fig. 6, the structure illustrated in Figs. 1A and 1B may be modified alternatively in accordance with the second aspect of the present invention so as to have a first semiconductive layer 4 and a second semiconductive layer 9a provided in place of the separated semiconductive layers 4a, 4b shown in Figs. 2A and 2B. The semiconductive layer 4 is comprised of silicon (Si) and formed between the buffer layer 3 and the electrode 6 and all over the buffer layer 3. The semiconductive layer 9a is comprised of silicon (Si) and formed between the semiconductive layer 4 and the electrode 5. Also, the semiconductive layer 9a has a specific resistance different from that of the semiconductive layer 4 and has a broader width than that of the corresponding electrode 5.

[0038] In the device using the asymmetrical electrodes 5, 6 for a traveling wave, the electric field in the vicinity of the optical waveguide 2b beneath the grounding electrode 6 is relatively weak. Therefore, even if a DC electric field is concentrated on the region between the electrodes 5 and 6, it is possible to suppress the influence exerted on the refractive index of the optical waveguide 2b beneath the electrode 6 and thus gain the same effect as above.

[0039] Figure 7 shows a structure of a first modification, which is an improvement of the example of Fig. 6.

[0040] In the present example, a semiconductive layer 9b comprised of silicon (Si) is added to the structure shown in Fig. 6. The semiconductive layer 9b is formed between the semiconductive layer 4 and the electrode 6. Also, the semiconductive layer 9b has a specific resistance different from that of the semiconductive layers 4, 9a and has a broader width than that of the corresponding electrode 6. Since the present device has a

number of design parameters, it is possible to design and optimize the device more effectively and thus gain a better effect.

[0041] Figures 8A and 8B show a structure of a second modification.

[0042] In addition to the features of the Fig. 7 structure, the structure of Figs. 8A and 8B has a semiconductive layer 9c, comprising silicon (Si), on which a third electrode 10 is formed, the layer 9c being separated from the layer 9a in a region between the electrodes 5 and 10. The semiconductive layer 9c has a specific resistance different from that of the semiconductive layer 4 and has a broader width than that of the electrode 10. According to this structure, it is possible to suppress a DC drift of the device and thus effectively compensate for a fluctuation in operational characteristics due to the DC drift, stress, or the like.

[0043] Although, in the above embodiments and the associated modifications, the explanation is given by way of reference to a Mach-Zehnder type modulator, the present invention is applicable to other optical waveguide devices such as optical switches, or the like. Also, the present invention can be applied to an optical waveguide device to which a low frequency signal and a high frequency signal are fed independently.

[0044] Although the present invention has been disclosed and described by way of various embodiments and the associated modifications, it is apparent to those skilled in the art that other embodiments and modifications of the present invention are possible.

Claims

1. An optical waveguide device comprising:

   an optical waveguide (2, 2a, 2b) formed on a surface of a substrate (1) having an electro-optical effect;
   a pair of electrodes (5, 6) operatively connected and arranged to receive a driving electric signal thereacross;
   a buffer layer (3) formed all over the said surface of said substrate (1) including the optical waveguide (2, 2a, 2b); and
   a semiconductive layer (4) formed between the buffer layer (3) and the pair of electrodes (5, 6), a part (P; Q) of the said semiconductive layer (4a, 4b; 4c) which corresponds to the gap between the pair of electrodes (5, 6) being of reduced or zero thickness;
   wherein a change in frequency of the driving electric signal applied across the pair of electrodes (5, 6) when the device is in use brings about a corresponding change in a distribution of an electric field which occurs in the vicinity of the optical waveguide (2, 2a, 2b), and wherein, when a low frequency electric signal is applied to the pair of electrodes (5, 6), the electric field is concentrated on the said part (P; Q) of the said semiconductive layer (4a, 4b; 4c).

2. An optical waveguide device as claimed in claim 1, wherein the semiconductive layer (4c) has a thinly-formed portion (Q) and is formed only in the vicinity of the pair of electrodes (5, 6).

3. An optical waveguide as claimed in claim 1, wherein when the thickness of said semiconductive layer (4a, 4b) at said part (P) is zero the semiconductive layer (4a, 4b) comprises two regions separated from one another at a part of said layer corresponding to the gap between the said pair of electrodes (5, 6), each separated region of the semiconductive layer (4a, 4b) having a broader width than that one of the said pair of electrodes (5, 6) under which it lies.

4. An optical waveguide device as claimed in claim 3, wherein that one (4a) of the separated regions (4a, 4b) of the semiconductive layer which underlies a signal line electrode (5) of the pair of electrodes (5, 6) is formed only in the vicinity of the signal line electrode (5).

5. An optical waveguide device comprising:

   an optical waveguide (2, 2a, 2b) formed on a surface of a substrate (1) having an electro-optical effect;
   a pair of electrodes (5, 6) operatively connected and arranged to receive a driving electric signal thereacross;
   a buffer layer (3) formed all over said surface of said substrate (1) including the optical waveguide (2, 2a, 2b); and
   a first semiconductive layer (4), formed between the buffer layer (3) and the pair of electrodes (5, 6), and a second semiconductive layer (9a), formed between the first semiconductive layer (4) and a signal line electrode (5) of the pair of electrodes (5, 6), the second semiconductive layer (9a) having a specific resistance different from that of the first semiconductive layer (4) and having a broader width than that of the signal line electrode (5);
   wherein a change in frequency of a driving electric signal applied therebetween when the device is in use brings about a corresponding change in a distribution of an electric field which occurs in the vicinity of the optical waveguide (2, 2a, 2b).

6. An optical waveguide device as claimed in claim 5, wherein a second semiconductive layer (9b) is also formed between the first semiconductive layer (4)

and a grounding electrode (6) of the pair of electrodes (5, 6) such that there are two semiconductive layer regions (9a, 9b) separated from one another at a location corresponding to the gap between the pair of electrodes (5, 6), each separated region (9a, 9b) having a broader width than that one of the said pair of electrodes (5, 6) under which it lies.

7. An optical waveguide device as claimed in claim 6, further comprising a third electrode (10), wherein a second semiconductive layer (9c) is also formed between the first semiconductive layer (4) and the said third electrode (10) such that there are three semiconductive layer regions (9a, 9b, 9c) separated from one another at respective locations corresponding to the gaps between the three electrodes (5, 6, 10), each separated region (9a, 9b, 9c) having a broader width than that one of the said electrodes (5, 6, 10) under which it lies.

8. An optical waveguide device as claimed in any preceding claim, wherein the buffer layer (3) comprises dielectric material and has a smaller refractive index than that of the optical waveguide (2, 2a, 2b).

9. An optical waveguide device as claimed in claim 8, wherein the dielectric material comprises silicon dioxide.

10. An optical waveguide device as claimed in any preceding claim, wherein the or each semiconductive layer (4; 9a, 9b) comprises silicon.

Patentansprüche

1. Optische Wellenleitervorrichtung mit:

   einem optischen Wellenleiter (2, 2a, 2b), der auf einer Oberfläche eines Substrates (1) gebildet ist, das einen elektrooptischen Effekt hat;
   einem Paar von Elektroden (5, 6), die operativ verbunden sind und angeordnet sind, um quer über sich ein elektrisches Steuersignal zu empfangen;
   einer Pufferschicht (3), die über der gesamten Oberfläche des Substrates (1) gebildet ist, die den optischen Wellenleiter (2, 2a, 2b) enthält; und
   einer halbleitenden Schicht (4), die zwischen der Pufferschicht (3) und dem Paar von Elektroden (5, 6) gebildet ist, wobei ein Teil (P; Q) der halbleitenden Schicht (4a, 4b; 4c), der dem Spalt zwischen dem Paar von Elektroden (5, 6) entspricht, eine reduzierte Dicke oder eine Dicke von Null hat;
   bei der eine Veränderung der Frequenz des elektrischen Steuersignals, das quer über das Paar von Elektroden (5, 6) angewendet wird, wenn die Vorrichtung in Gebrauch ist, eine entsprechende Veränderung einer Verteilung eines elektrischen Feldes bewirkt, das in der Nähe des optischen Wellenleiters (2, 2a, 2b) auftritt, und bei der dann, wenn ein elektrisches Niederfrequenzsignal auf das Paar von Elektroden (5, 6) angewendet wird, das elektrische Feld auf den genannten Teil (P; Q) der halbleitenden Schicht (4a, 4b; 4c) konzentriert wird.

2. Optische Wellenleitervorrichtung nach Anspruch 1, bei der die halbleitende Schicht (4c) einen dünn gebildeten Abschnitt (Q) hat und nur in der Nähe des Paares von Elektroden (5, 6) gebildet ist.

3. Optischer Wellenleiter nach Anspruch 1, bei dem dann, wenn die Dicke der halbleitenden Schicht (4a, 4b) in dem genannten Teil (P) Null ist, die halbleitende Schicht (4a, 4b) zwei Zonen umfaßt, die an einem Teil der Schicht, der dem Spalt zwischen dem Paar von Elektroden (5, 6) entspricht, voneinander getrennt sind, wobei jede getrennte Zone der halbleitenden Schicht (4a, 4b) eine größere Breite als diejenige des Paares von Elektroden (5, 6) hat, unter der sie liegt.

4. Optische Wellenleitervorrichtung nach Anspruch 3, bei der diejenige (4a) der getrennten Zonen (4a, 4b) der halbleitenden Schicht, die unter einer Signalleitungselektrode (5) des Paares von Elektroden (5, 6) liegt, nur in der Nähe der Signalleitungselektrode (5) gebildet ist.

5. Optische Wellenleitervorrichtung mit:

   einem optischen Wellenleiter (2, 2a, 2b), der auf einer Oberfläche eines Substrates (1) gebildet ist, das einen elektrooptischen Effekt hat;
   einem Paar von Elektroden (5, 6), die operativ verbunden sind und angeordnet sind, um quer über sich ein elektrisches Steuersignal zu empfangen;
   einer Pufferschicht (3), die über der gesamten Oberfläche des Substrates (1) gebildet ist, die den optischen Wellenleiter (2, 2a, 2b) enthält; und
   einer ersten halbleitenden Schicht (4), die zwischen der Pufferschicht (3) und dem Paar von Elektroden (5, 6) gebildet ist, und einer zweiten halbleitenden Schicht (9a), die zwischen der ersten halbleitenden Schicht (4) und einer Signalleitungselektrode (5) des Paares von Elektroden (5, 6) gebildet ist, welche zweite halbleitende Schicht (9a) einen spezifischen Widerstand hat, der sich von jenem der ersten halbleitenden Schicht (4) unterscheidet, und eine größere Breite als die Signalleitungselektrode (5) hat;

bei der eine Veränderung der Frequenz eines elektrischen Steuersignals, das dazwischen angewendet wird, wenn die Vorrichtung in Gebrauch ist, eine entsprechende Veränderung einer Verteilung eines elektrischen Feldes bewirkt, das in der Nähe des optischen Wellenleiters (2, 2a, 2b) auftritt.

6. Optische Wellenleitervorrichtung nach Anspruch 5, bei der eine zweite halbleitende Schicht (9b) auch zwischen der ersten halbleitenden Schicht (4) und einer Erdelektrode (6) des Paares von Elektroden (5, 6) gebildet ist, so daß zwei Zonen der halbleitenden Schicht (9a, 9b) vorhanden sind, die an einer Stelle voneinander getrennt sind, die dem Spalt zwischen dem Paar von Elektroden (5, 6) entspricht, wobei jede getrennte Zone (9a, 9b) eine größere Breite als diejenige des genannten Paares von Elektroden (5, 6) hat, unter der sie liegt.

7. Optische Wellenleitervorrichtung nach Anspruch 6, ferner mit einer dritten Elektrode (10), bei der eine zweite halbleitende Schicht (9c) auch zwischen der ersten halbleitenden Schicht (4) und der dritten Elektrode (10) gebildet ist, so daß drei Zonen der halbleitenden Schicht (9a, 9b, 9c) vorhanden sind, die an jeweiligen Stellen, die den Spalten zwischen den drei Elektroden (5, 6, 10) entsprechen, voneinander getrennt sind, wobei jede getrennte Zone (9a, 9b, 9c) eine größere Breite als diejenige der Elektroden (5, 6, 10) hat, unter der sie liegt.

8. Optische Wellenleitervorrichtung nach irgendeinem vorhergehenden Anspruch, bei der die Pufferschicht (3) dielektrisches Material umfaßt und einen kleineren Brechungsindex als der optische Wellenleiter (2, 2a, 2b) hat.

9. Optische Wellenleitervorrichtung nach Anspruch 8, bei der das dielektrische Material Siliciumdioxid umfaßt.

10. Optische Wellenleitervorrichtung nach irgendeinem vorhergehenden Anspruch, bei der die oder jede halbleitende Schicht (4; 9a, 9b) Silicium umfaßt.

Revendications

1. Dispositif de guide d'onde optique comprenant :

   un guide d'onde optique (2, 2a, 2b) formé sur une surface d'un substrat (1) ayant un effet électro-optique ;
   une paire d'électrodes (5, 6) connectées de façon fonctionnelle et agencées pour recevoir entre elles un signal électrique d'attaque ;
   une couche tampon (3) formée sur toute ladite surface dudit substrat (1) y compris le guide d'onde optique (2, 2a, 2b) ; et
   une couche semi-conductrice (4) formée entre la couche tampon (3) et la paire d'électrodes (5, 6), une partie (P ; Q) de ladite couche semi-conductrice (4a, 4b ; 4c) qui correspond à l'espace entre la paire d'électrodes (5, 6) étant d'une épaisseur réduite ou nulle ;
   dans lequel une variation de fréquence du signal électrique d'attaque appliqué entre la paire d'électrodes (5, 6), lorsque le dispositif est en utilisation, provoque une variation correspondante de la répartition d'un champ électrique qui apparaît au voisinage du guide d'onde optique (2, 2a, 2b), et dans lequel, lorsque l'on applique un signal électrique à basse fréquence à la paire d'électrodes (5, 6), le champ électrique est concentré sur ladite partie (P ; Q) de ladite couche semi-conductrice (4a, 4b ; 4c).

2. Dispositif de guide d'onde optique selon la revendication 1, dans lequel la couche semi-conductrice (4c) comporte une partie (Q) formée finement et est formée seulement au voisinage de la paire d'électrodes (5, 6).

3. Dispositif de guide d'onde optique selon la revendication 1, dans lequel, lorsque l'épaisseur de ladite couche semi-conductrice (4a, 4b) au niveau de ladite partie (P) est nulle, la couche semi-conductrice (4a, 4b) comprend deux régions séparées l'une de l'autre au niveau d'une partie de ladite couche correspondant à l'espace entre ladite paire d'électrodes (5, 6), chaque région séparée de la couche semi-conductrice (4a, 4b) ayant une largeur plus grande que celle de ladite paire d'électrodes (5, 6) sous laquelle elle se trouve.

4. Dispositif de guide d'onde optique selon la revendication 3, dans lequel celle (4a) des régions séparées (4a, 4b) de la couche semi-conductrice qui se trouve sous une électrode (5) de ligne de signal de la paire d'électrodes (5, 6) est formée seulement au voisinage de l'électrode (5) de ligne de signal.

5. Dispositif de guide d'onde optique comprenant :

   un guide d'onde optique (2, 2a, 2b) formé sur une surface d'un substrat (1) ayant un effet électro-optique ;
   une paire d'électrodes (5, 6) connectées de façon fonctionnelle et agencées pour recevoir entre elles un signal électrique d'attaque ;
   une couche tampon (3) formée sur toute ladite surface dudit substrat (1) y compris le guide d'onde optique (2, 2a, 2b) ; et
   une première couche semi-conductrice (4) formée entre la couche tampon (3) et la paire

d'électrodes (5, 6), et une seconde couche semi-conductrice (9a), formée entre la première couche semi-conductrice (4) et une électrode (5) de ligne de signal de la paire d'électrodes (5, 6), la seconde couche semi-conductrice (9a) ayant une résistance spécifique différente de celle de la première couche semi-conductrice (4) et ayant une largeur plus grande que celle de l'électrode (5) de ligne de signal ;
dans lequel une variation de fréquence d'un signal électrique d'attaque appliqué entre les deux, lorsque le dispositif est en utilisation, provoque une variation correspondante de la répartition d'un champ électrique qui apparaît au voisinage du guide d'onde optique (2, 2a, 2b).

6. Dispositif de guide d'onde optique selon la revendication 5, dans lequel une deuxième couche semi-conductrice (9b) est aussi formée entre la première couche semi-conductrice (4) et l'électrode (6) de mise à la masse de la paire d'électrodes (5, 6), de façon qu'il y ait deux régions (9a, 9b) de couche semi-conductrice séparées l'une de l'autre au niveau d'un emplacement correspondant à l'espace entre la paire d'électrodes (5, 6), chaque région séparée (9a, 9b) ayant une largeur plus grande que celle de l'électrode, de ladite paire d'électrodes (5, 6), sous laquelle elle se trouve.

7. Dispositif de guide d'onde optique selon la revendication 6, comprenant en outre une troisième électrode (10), dans lequel une seconde couche semi-conductrice (9c) est aussi formée entre la première couche semi-conductrice (4) et ladite troisième électrode (10), de façon qu'il y ait trois régions (9a, 9b, 9c) de couche semi-conductrice séparées les unes des autres au niveau d'emplacements respectifs correspondant aux espaces entre les trois électrodes (5, 6, 10), chaque région séparée (9a, 9b, 9c) ayant une largeur plus grande que celle de l'électrode, desdites électrodes (5, 6, 10), sous laquelle elle se trouve.

8. Dispositif de guide d'onde optique selon l'une quelconque des revendications précédentes, dans lequel la couche tampon (3) est composée d'une matière diélectrique et a un indice de réfraction plus petit que celui du guide d'onde optique (2, 2a, 2b).

9. Dispositif de guide d'onde optique selon la revendication 8, dans lequel la matière diélectrique comprend du dioxyde de silicium.

10. Dispositif de guide d'onde optique selon l'une quelconque des revendications précédentes, dans lequel la, ou chaque, couche semi-conductrice (4 ; 9a, 9b) comprend du silicium.

Fig. 1A

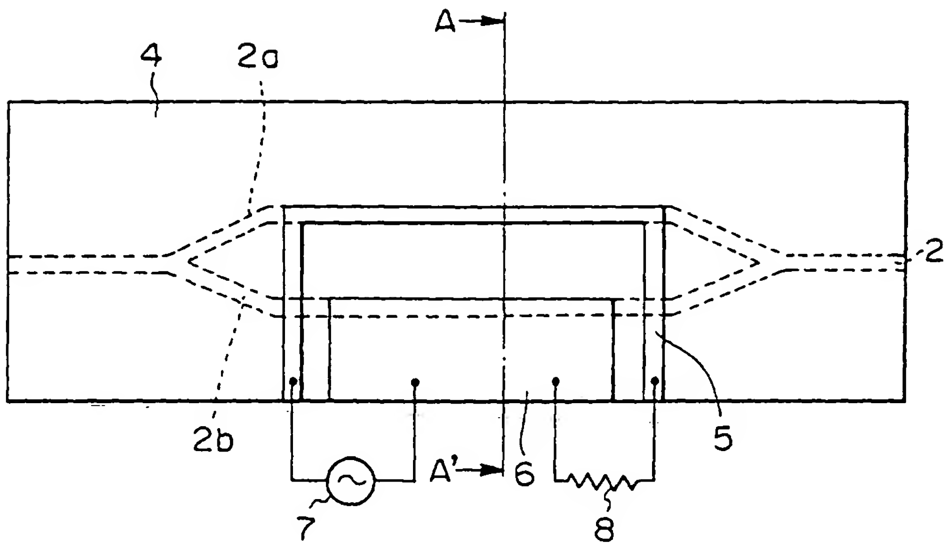


Fig. 1B

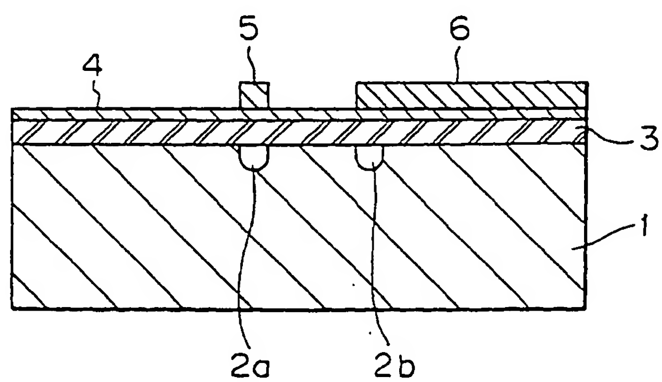


Fig. 2A

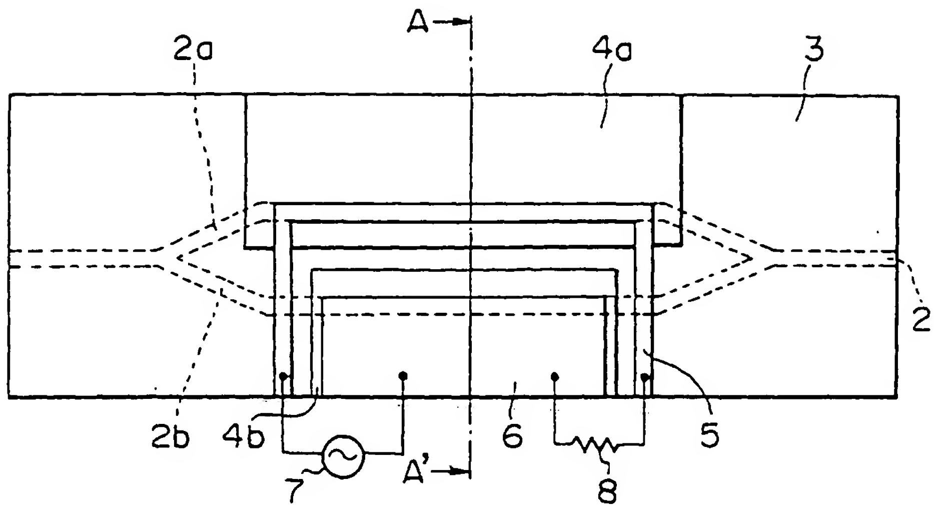


Fig. 2B

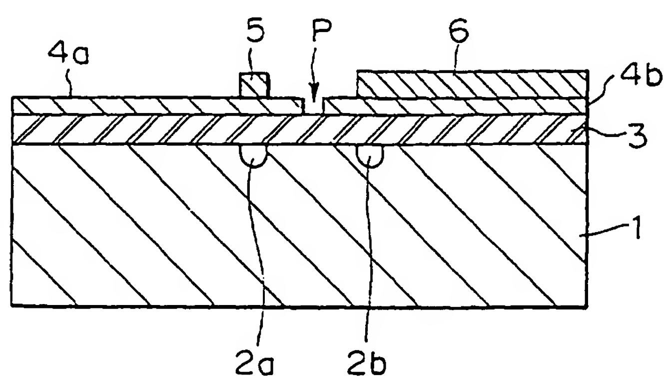


Fig. 3

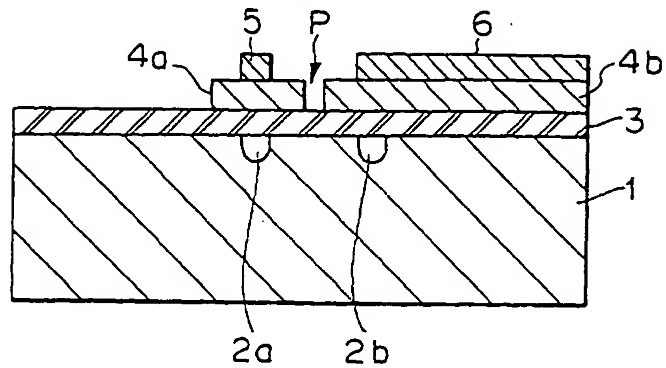


Fig. 4

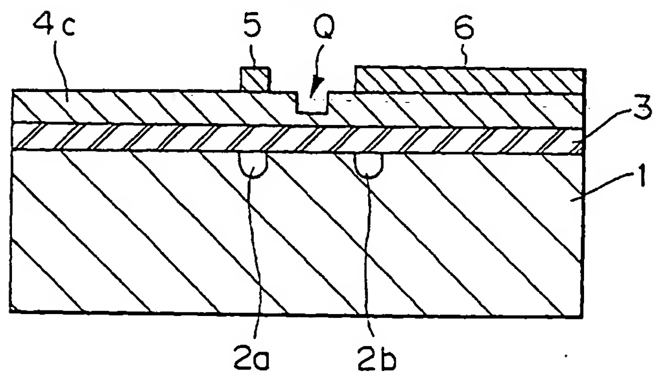


Fig. 5

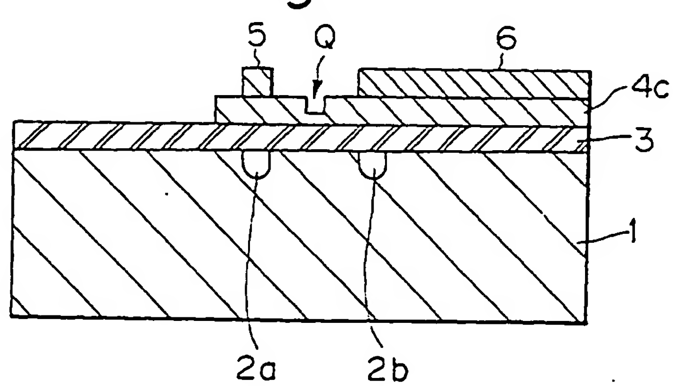


Fig. 6

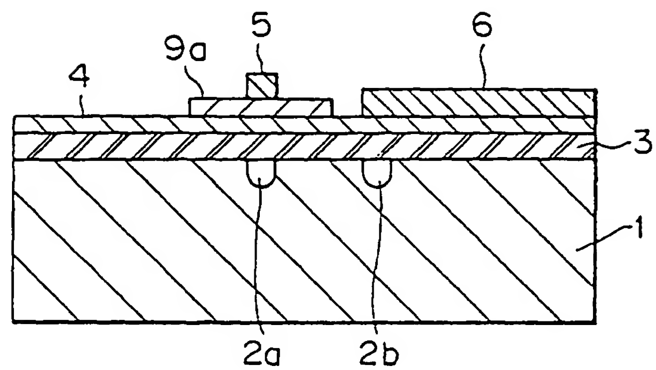


Fig. 7

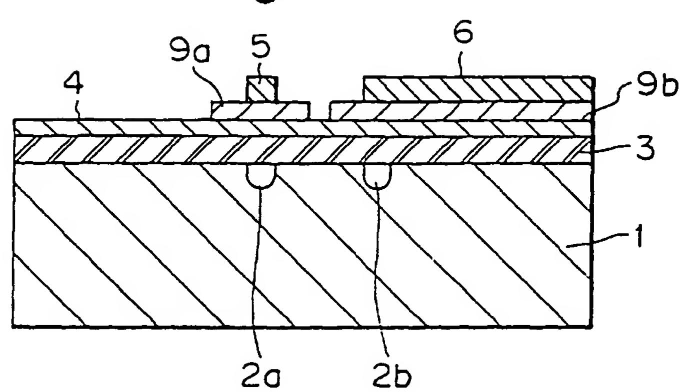


Fig. 8A

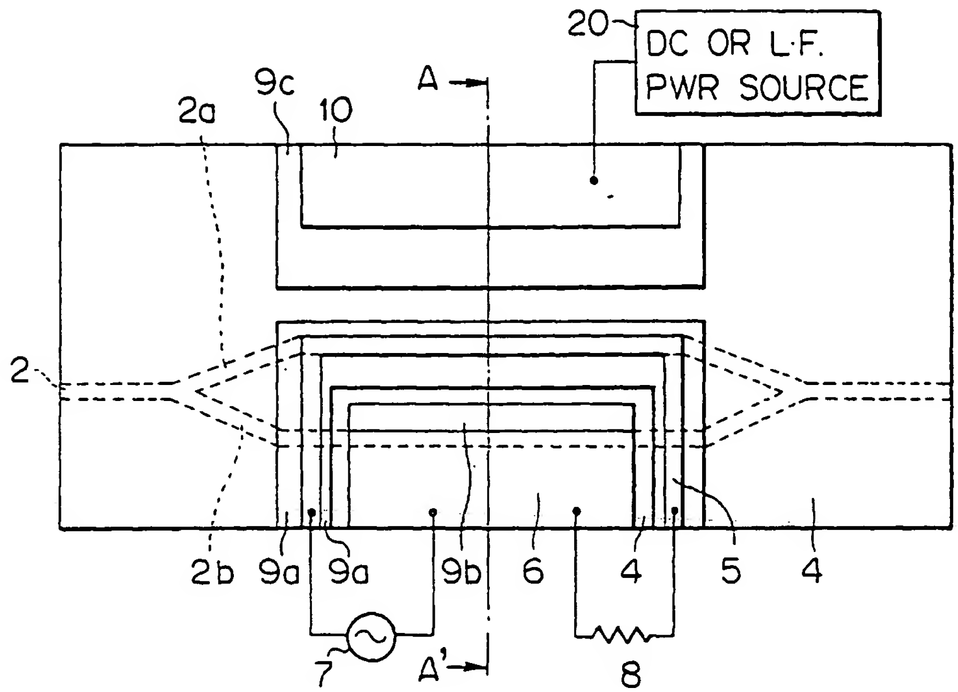
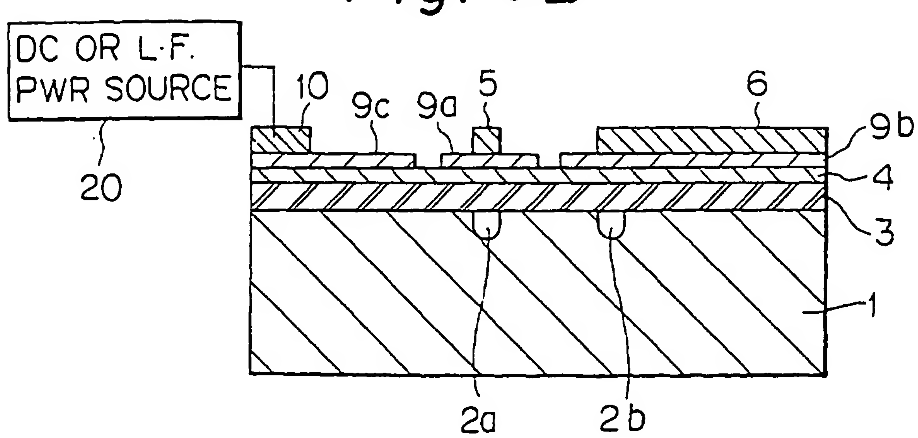

20
DC OR L·F.
PWR SOURCE
9c
A
2a
10
2
2b
9a
9a
9b
6
4
5
4
7
A'
8

Fig. 8B


DC OR L·F.
PWR SOURCE
20
10
9c
9a
5
6
9b
4
3
1
2a
2b

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*                            L     S   S   T    ::                                *
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*                                                                                 *
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US005535045A

United States Patent [19]

Dutta et al.

[11] Patent Number: 5,535,045

[45] Date of Patent: Jul. 9, 1996

[54] **MODULATION DOPED QUANTUM WELL WAVEGUIDE MODULATOR**

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[73] Assignee: **The United States of America as represented by the Secretary of the Army**, Washington, D.C.

[21] Appl. No.: **214,730**

[22] Filed: **Mar. 17, 1994**

[51] **Int. Cl.**[6] **G02F 1/03**

[52] **U.S. Cl.** **359/248**; 359/245

[58] **Field of Search** 257/17, 22, 14, 257/86, 85; 359/245, 248

[56] **References Cited**

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Zucker et al, "Compact Low–Voltage InGaAs/InAlAs Multiple Quantum Well Waveguide Interferometers", Electronics Letters, vol. 26, no. 24, pp. 2029–2031, 22 Nov. 1990.

Primary Examiner—David C. Nelms
Assistant Examiner—F. Niranjan
Attorney, Agent, or Firm—Michael Zelenka; William H. Anderson

[57] **ABSTRACT**

The dielectric constant and the optical properties of a semiconductor device are changed by tuning the electron density in modulation doped quantum wells. The quantum wells are formed in an "i" region of a p-i-n structure having, in sequence, a 150 Å wide GaAs quantum well, a wider $Al_xGa_{1-x}As$ barrier with a central silicon doped section and an undoped AlGaAs barrier with a slightly higher barrier height to prevent transfer of carriers to the next well. When a reverse bias is applied, more D centers are tuned below the Fermi level so that they can trap electrons from the wells, thereby reducing electron density and changing the optical properties of the material.

17 Claims, 2 Drawing Sheets

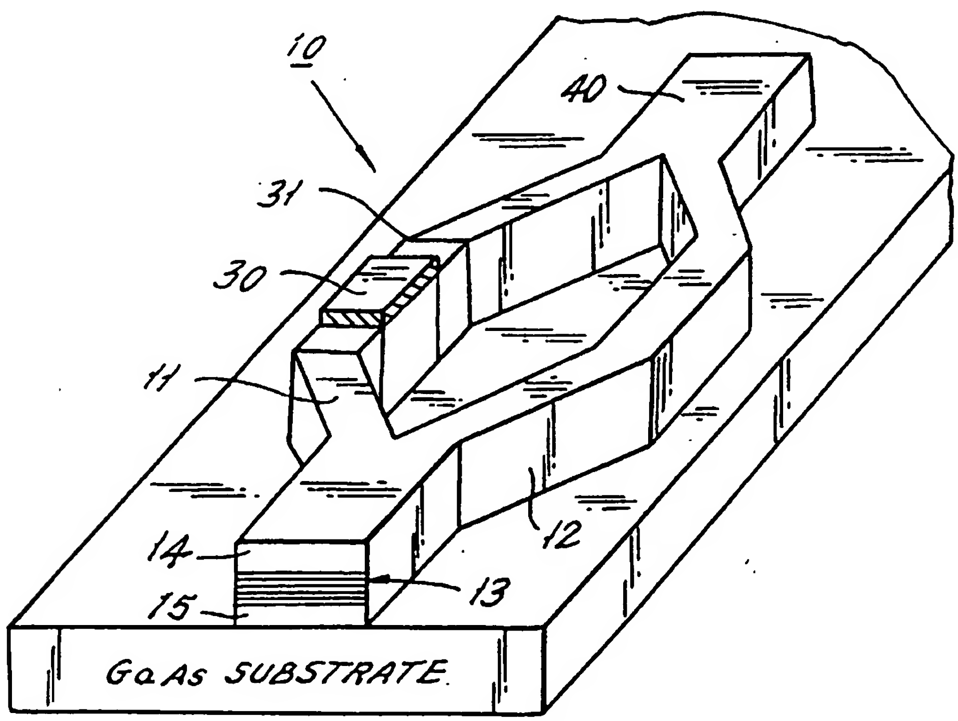


FIG. 1

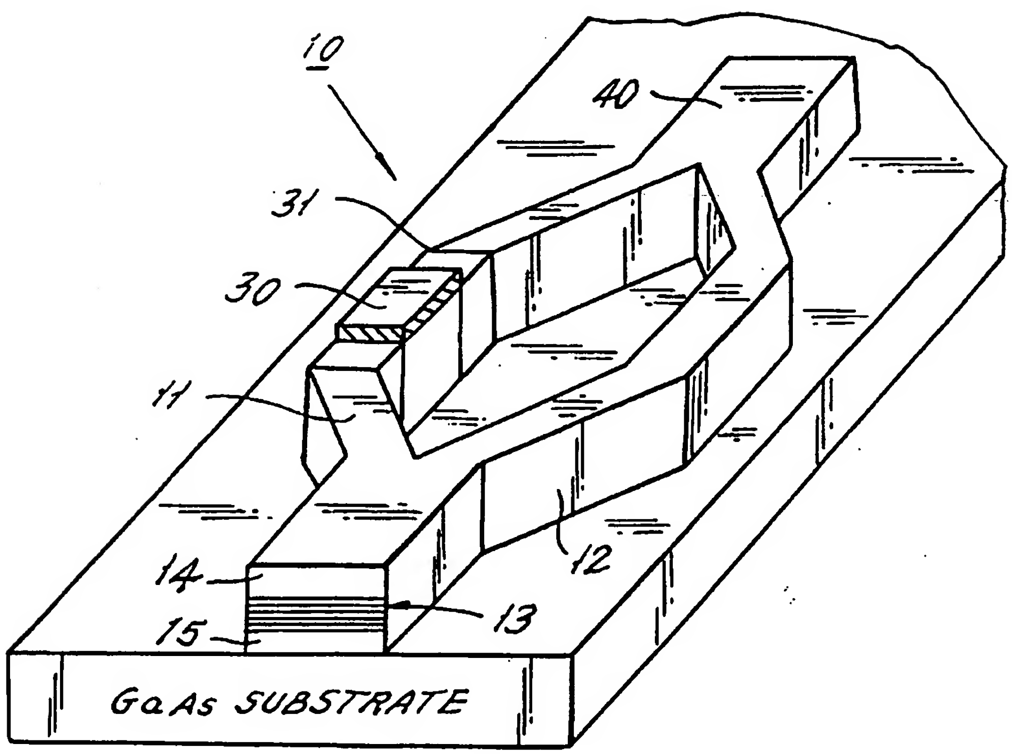


FIG. 2

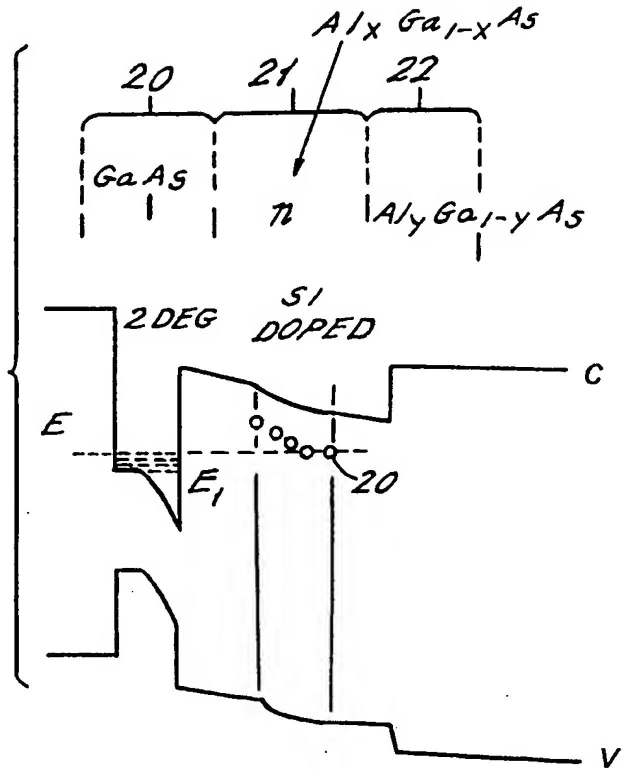
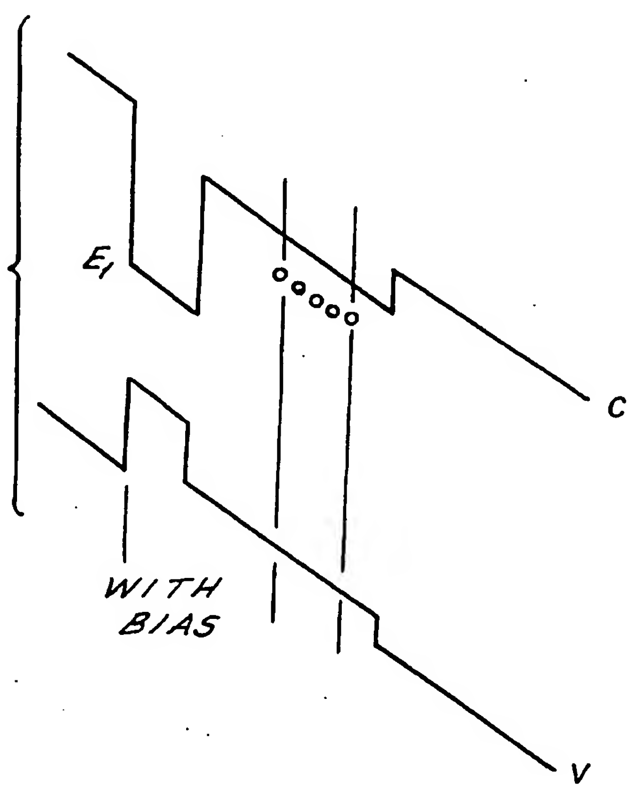

Al x Ga 1-x As
20
21
22
GaAs
n
Al y Ga 1-y As
2DEG
SI DOPED
C
E
E1
20
V

FIG. 3


E1
C
WITH BIAS
V

MODULATION DOPED QUANTUM WELL WAVEGUIDE MODULATOR

GOVERNMENT INTEREST

The invention described herein may be manufactured, used, and licensed by or for the Government of the United States of America without the payment to us of any royalty thereon.

BACKGROUND OF THE INVENTION

This invention relates to optical waveguides, and more specifically relates to a novel semiconductor heterostructure for optical waveguides.

A large number of applications exist for miniaturized optical waveguide modulators, such as waveguide phase modulators, intensity modulators and interferometers. Specific relevant prior art includes Zucher et al. (infra), wherein the use of a barrier reservoir and quantum well electron transfer structure (BRAQWETS) is known for a Mach Zehnder interferometer, having a phase modulator in one of two split waveguides as described by Zucker et al, "Multi-Gigahertz Bandwidth Intensity Modulators Having Tunable Electron-Density Multiple Quantum Well Waveguides", Phys. Lett., Vol. 59, 201–203 (1990) and Zucker et al. Electron Lett. 26, 2029 (1990).

BRIEF SUMMARY OF THE INVENTION

The present invention provides a novel tunable electron density mechanism to make a controlled change in the optical properties of an optical waveguide. Real tuning of the electron density is employed. More specifically, the novel modulator consists of a semiconductor heterostructure having multiple GaAs/AlGaAs quantum well modulation doped by silicon in one side of the barrier. The quantum wells are sandwiched in a regular waveguide with a p-i-n structure.

However, unlike a BRAQWETS structure, the modulator structure of the invention provides a gradual change of the optical properties, i.e., refractive index, in the waveguide by gradually changing the applied bias. By doing this, the difficulty in material growth of the quaternary InGaAlAs, which is necessary for the BRAQWETS structure, is overcome.

In the preferred embodiment of the invention, there is a 150 Å wide GaAs well atop a wider first $Al_xGa_{1-x}As$ barrier, in which x is equal to or greater than 20%. The AlGaAs barrier has a central silicon doped portion, with a 100 Å undoped spacer on each side. A further undoped AlGaAs barrier is atop the first barrier and has a slightly higher barrier to ordinarily prevent the transfer of carriers to the next well.

By making the fraction x in the first AlGaAs barrier equal to or larger than 22%, a significant number of silicon donors form DX centers when a reverse bias is applied.

Without bias, most silicon donors are ionized, giving electrons to the wells to form the two dimensional electron gas that causes an asymmetric band bending in both well and barrier. The lowest point of DX level is pinned to the Fermi level so that they can trap the electrons from the wells at room temperature, thus reducing the electron density.

When the density of the two dimensional electron gas is changed in the modulation doped wells, the optical properties of the material, such as the absorption edge and the refractive index, changes, thereby changing the phase of light propagating through the material. Thus, tuning the electron density causes a phase change in the waveguide structure.

Since this waveguide modulator may provide a controllable gradual phase shift for the guided light, the present invention has a wide application to miniaturized optical devices such as a Mach Zehnder rib waveguide interferometer or the like, and permits the integration of a microspectrometer into small semiconductor chips. Such devices will have miniature size and low cost and can be used in such applications as target recognition (by color), chemical analysis, remote sensing of any type, spectroscopy in general and in robotics applications.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective diagram of a preferred embodiment of the invention, in which the multiple one-sided doped GaAs/AlGaAs asymmetric quantum well structure is used as the waveguiding layer built into a Mach Zehnder rib waveguide interferometer.

FIG. **2** is a diagram showing the energy level of the modulation doped quantum well of FIG. **1** without bias.

FIG. **3** shows the diagram of FIG. **2** with bias applied, to modulate the optical characteristics of the device of FIG. **1**.

DETAILED DESCRIPTION OF THE DRAWINGS

Referring first to FIG. **1**, there is shown a first embodiment of the invention as a Mach Zehnder rib waveguide interferometer **10** having two legs **11** and **12**. The semiconductor heterostructure for the modulator **13** is a multiple GaAs/AlGaAs quantum well modulation doped by silicon in one side of the barrier. The quantum wells are sandwiched in a regular waveguide with a p-i-n structure. Thus, in FIG. **1**, there is a top P-type AlGaAs cladding layer **14** and a low N-type AlGaAs cladding layer **15**.

The multiple one-sided modulation doped quantum wells of FIG. **1** have the structure best understood from FIG. **2** and consists of an approximately 150 Å wide GaAs quantum well **20**, a wide $Al_xGa_{1-x}As$ barrier atop the GaAs layer **21** and a second, but undoped, barrier $Al_yGa_{1-y}As$ layer **22**, atop layer **22**. If the Al fraction x is equal to or larger than 22%, significant silicon donors form DX centers. The percentage y in the $Al_yGa_{1-y}As$ is greater than x by about 5%. The silicon doping is greater or equal to about $10^{18}cm^{-3}$. The quantum wells are repeated five to ten times.

The second barrier **21** has a slightly higher barrier height to prevent the transfer of carriers to the next well in the stack.

When no bias is applied, as in FIG. **2**, most silicon donors are ionized, giving an electron to the wells to form the two-dimensional electron gas which causes an asymmetric band bending in both well and barrier. The lowest point of the DX level **20** shown in FIG. **2** is pinned at the Fermi level as shown.

When the reverse bias is applied, more DX centers are tuned below the Fermi level so they can trap more electrons from the wells at room temperature, as shown in FIG. **3**, thereby reducing the electron density.

When the density of the two dimensional electron gas is changed in the modulation doped wells, the absorption edge changes which, in turn, changes the dielectric constant of the material and changes the phase of light propagating in the material. Therefore, tuning the electron density makes the phase change in the waveguide structure of FIG. **1**.

The manufacture of the device of FIG. 1 can obviously employ conventional lithographic definition and etching techniques. An active phase modulation section 30 is formed on the central portion of rib 11 by a metal contact layer and an electrical isolation of the P-type cladding 31, and using H-ion implantation to electrically isolate the active phase modulation section from the rest of the waveguide.

By applying a voltage, the phase of the light may be modulated due to a change in properties of the material, i.e., the refractive index and absorption edge.

In operation, incident light is split between legs or ribs 11 and 12, and the light in leg 11 is phase shifted by the modulator relative to that in leg 12. Interference is then produced at the joining output 40 in a variably controlled manner.

In a preferred embodiment of the invention, an electron transfer quantum well waveguide phase modulator consists of an n type substrate which carries a bottom cladding layer of $Al_{0.44}GaAs$ which may have a thickness of 1 to 1.5 micrometers and a concentration of $1-5\times10^{18}/cm^{-3}$.

The core guiding layer is formed atop the guiding layer and consists, from bottom up, of the following basic structure which is repeated five to ten times:

$Al_yGa_{1-y}As$ (undoped) (500 Å);

$Al_yGa_{1-x}As$ (undoped) (50 Å);

$Al_xGa_{1-x}As$ n $(1-5\times10^{18}/cm^{-3})$ (200–600 Å)

$Al_xGa_{1-x}As$ (undoped) (100–200 Å)

GaAs (undoped) (100–150 Å)

In the above, $x \geqq 22\%$; $y \geqq x+5\%$

The top cladding layer consists of three layers which are, from the bottom up:

$Al_{0.44}Ga_{0.66}As$ $(P^+)(Be\sim5\times10^{18})$ cm^{-3} (1–1.5 μm)

$Al_{0.44}Ga_{0.66}As$ $(P^+)(Be\sim5\times10^{18})$ cm^{-3}(~1000 Å)

$GaAs(P^+)$ $(Be\sim5\times10^{18}cm^{-3})$ (~500 Å)

As those skilled in the art will appreciate from this, the device so formed in FIG. 1 can then be used in applications of a Mach Zehnder interferometer, or in waveguide light intensity modulators, multiple wavelength microspectrometers and the like.

Although the present invention has been described in relation to particular embodiments thereof, many other variations and modifications and other uses will become apparent to those skilled in the art. It is preferred, therefore, that the present invention be limited not by the specific disclosure herein, but only by the appended claims.

What is claimed is:

1. A modulation doped quantum well waveguide modulator comprising, in combination:

a) a first thin planar GaAs quantum well layer;

b) a second thin $Al_xGa_{1-x}As$ barrier layer disposed atop said GaAs quantum well layer;

c) a third thin AlGaAs barrier layer disposed atop said $Al_xGa_{1-x}As$ barrier layer, wherein x is equal to or greater than 20%;

d) a silicon doped N region disposed in the center of said $Al_xGa_{1-x}As$ barrier layer.

2. The device of claim 1 wherein said layers of GaAs, $Al_xGa_{1-x}As$ and AlGaAs are coextensive with one another.

3. The device of claim 1 wherein said GaAs quantum well layer has a thickness of about 150 Å; said $Al_xGa_{1-x}As$ barrier layer has 100 Å regions on either side of said silicon doped N region.

4. The device of claim 2 wherein said GaAs quantum well layer has a thickness of about 150 Å; said $Al_xGa_{1-x}As$ barrier layer has 100 Å regions on either side of said silicon doped N region.

5. The device of claim 1 wherein said AlGaAs layer has a higher barrier than that of said $Al_xGa_{1-x}As$ layer.

6. The device of claim 3 wherein said AlGaAs layer has a higher barrier than that of said $Al_xGa_{1-x}As$ layer.

7. The device of claim 6 wherein said layers of GaAs, $Al_xGa_{1-x}As$ and AlGaAs are coextensive with one another.

8. The device of claim 1 which contains a plurality of sets of said first, second and third layers.

9. The device of claim 8 wherein said layers of GaAs, $Al_xGa_{1-x}As$ and AlGaAs are coextensive with one another.

10. The device of claim 9 wherein said GaAs quantum well layer has a thickness of about 150 Å; said $Al_xGa_{1-x}As$ barrier layer has 100 Å regions on either side of said silicon doped N region.

11. The device of claim 9 wherein said AlGaAs layer has a higher barrier than that of said $Al_xGa_{1-x}As$ layer.

12. The device of claim 8 which further has a layer of P type cladding on top of the free surface of said AlGaAs layer, and a layer of N type cladding on the bottom of said layer of said third AlGaAs.

13. The device of claim 2 which further has a layer of P type cladding on top of the free surface of said AlGaAs layer, and a layer of N type cladding on the bottom of said layer of said third AlGaAs.

14. The device of claim 3 which further has a layer of P type cladding on top of the free surface of said AlGaAs layer, and a layer of N type cladding on the bottom of said layer of said third AlGaAs.

15. The device of claim 5 which further has a layer of P type cladding on top of the free surface of said AlGaAs layer, and a layer of N type cladding on the bottom of said layer of said third AlGaAs.

16. An electron-transfer modulation doped, quantum well, waveguide phase modulator comprising:

an active modulation doped multiple quantum well waveguiding core formed of alternating layers of AlGaAs and GaAs;

a p-type doped AlGaAs cladding region disposed on one side of said waveguiding core;

an n-type doped AlGaAs cladding region disposed on the other side of said waveguiding core; and

an n-type GaAs substrate disposed adjacent said n-type doped cladding region,

wherein the waveguiding core includes a plurality of layers which each contain:

(a) a planar GaAs undoped quantum well layer between 100 Å and 200 Å in width;

(b) a first undoped $Al_xGa_{1-x}As$ barrier between 100 Å and 200 Å, wherein x is greater than 20% and wherein said first undope barrier serves as a spacer layer which is disposed below said quantum well layer;

(c) an n-type Si-doped $Al_xGa_{1-x}As$ barrier between 200 Å and 400 Å in width, wherein said Si-doped barrier is disposed under said first undoped barrier and is doped to approximately $1-5\times10^{18}cm^{-3}$;

(d) a second undoped $Al_xGa_{1-x}As$ barrier approximately 50 Å in width, said second undoped barrier being disposed below the Si-doped barrier;

(e) a second doped $Al_yGa_{1-y}As$ wherein $y \geqq x+5\%$ and wherein said second undoped barrier is disposed below the second undoped barrier and is approximately 500 Å; and

(f) an interim undoped $Al_yGa_{1-y}As$ barrier which is approximately 500 Å; wherein said interim layer is

disposed between said p-type cladding region and the waveguiding core.

17. An electron-transfer modulation doped, quantum well, waveguide phase modulator comprising:

an active modulation doped multiple quantum well waveguiding core formed of alternating layers of AlGaAs and GaAs;

a p-type doped AlGaAs cladding region disposed on one side of said waveguiding core;

an n-type doped AlGaAs cladding region disposed on the other side of said waveguiding core; and

an n-type GaAs substrate disposed adjacent said n-type doped cladding region,

wherein the p-type cladding region includes a 1 to 1.5 micrometer AlGaAs p-type beryllium doped layer wherein a AlAs fraction is larger than y, a second p^+-type doped AlGaAs layer which is 1000 Å in width, and thin p^+-GaAs layer which serves as a cap layer.

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